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CREEP FATIGUE LIFE PREDICTION FOR ENGINE HOT SECTION MATERIALS (ISOTROPIC) FIFTH YEAR PROGRESS REVIEW*

Richard S. Nelson and Peter R. Harvey
Pratt & Whitney Division
United Technologies Corporation
East Hartford, Connecticut

As gas turbine technology continues to advance, the need for advanced life prediction methods for hot section components is becoming more and more evident. The complex local strain and temperature histories at critical locations must be accurately interpreted to account for the effects of various damage mechanisms (such as fatigue, creep, and oxidation) and their possible interactions. As part of the overall NASA HOST effort, this program is designed to investigate these fundamental damage processes, identify modeling strategies, and develop practical models which can be used to guide the early design and development of new engines and to increase the durability of existing engines.

This contract has recently been modified to be a 6-year effort, consisting of a 2-year base program and a 4-year option program. Two different isotropic materials (B1900+Hf and INCO 718) will be used, along with two protective coating systems (overlay and diffusion aluminide). The base program, which was completed during 1984, included comparison and evaluation of several popular high-temperature life prediction approaches as applied to continuously cycled isothermal specimen tests. The optional program, of which three years have been completed, is designed to develop models that can account for complex cycles and loadings, such as thermomechanical cycling, cumulative damage, multiaxial stress/strain states, and environmental effects. The base program has already been discussed in reference 1 and therefore no additional review of that work will be presented in this paper.

THERMOMECHANICAL MODEL DEVELOPMENT

A significant task under the option program is the development of a life prediction model which is valid under conditions of thermomechanical fatigue (TMF). The specimen testing under this task was completed in December, 1986, with a total of 55 B1900+Hf TMF specimen tests. Of these, 32 specimens were tested in the uncoated condition, 12 had NiCoCrAlY overlay coating, and 11 had

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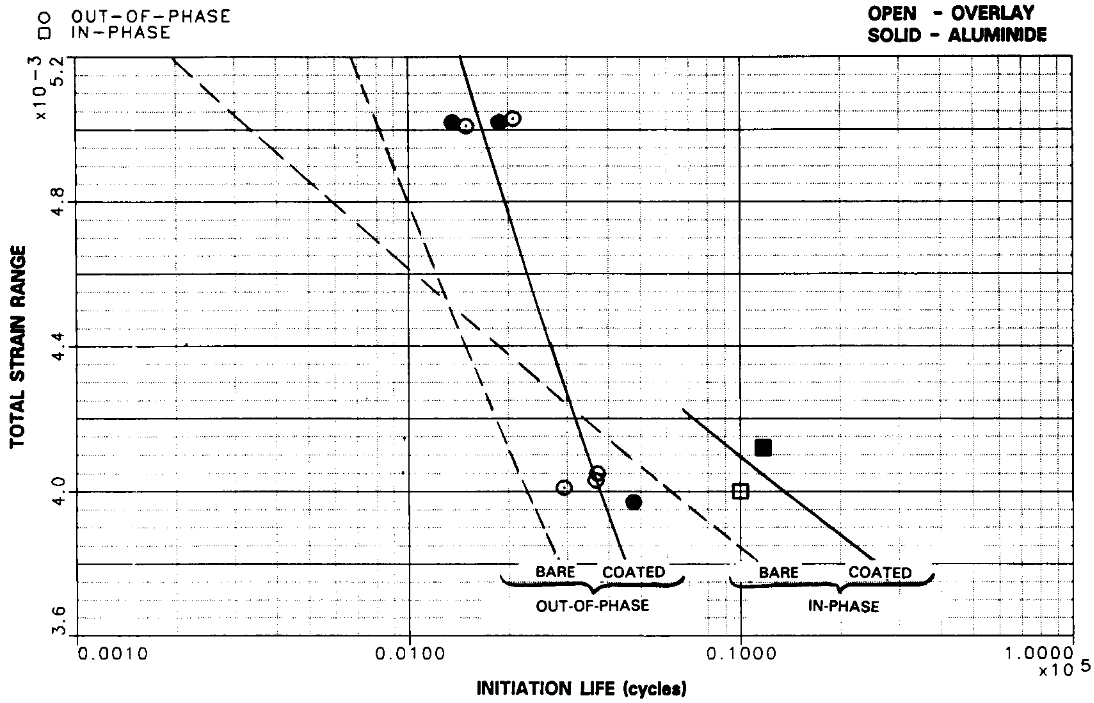
diffusion aluminide coating. The test variables included strain range, temperature range, mean strain, cycle type, and hold times. The conditions were chosen to complement both the uncoated TMF tests and the baseline isothermal fatigue tests. Particular attention was focused on the low strain, high life regime, since modern turbomachinery is typically designed for good durability. Some of the non-standard cycle types used (such as elliptical and dogleg cycles) have demonstrated that TMF damage cannot always be predicted in the same manner as isothermal tests. The model chosen must be sensitive to accumulation of damage from any arbitrary strain-stress-temperature cycle and yet be practical for use in design applications.

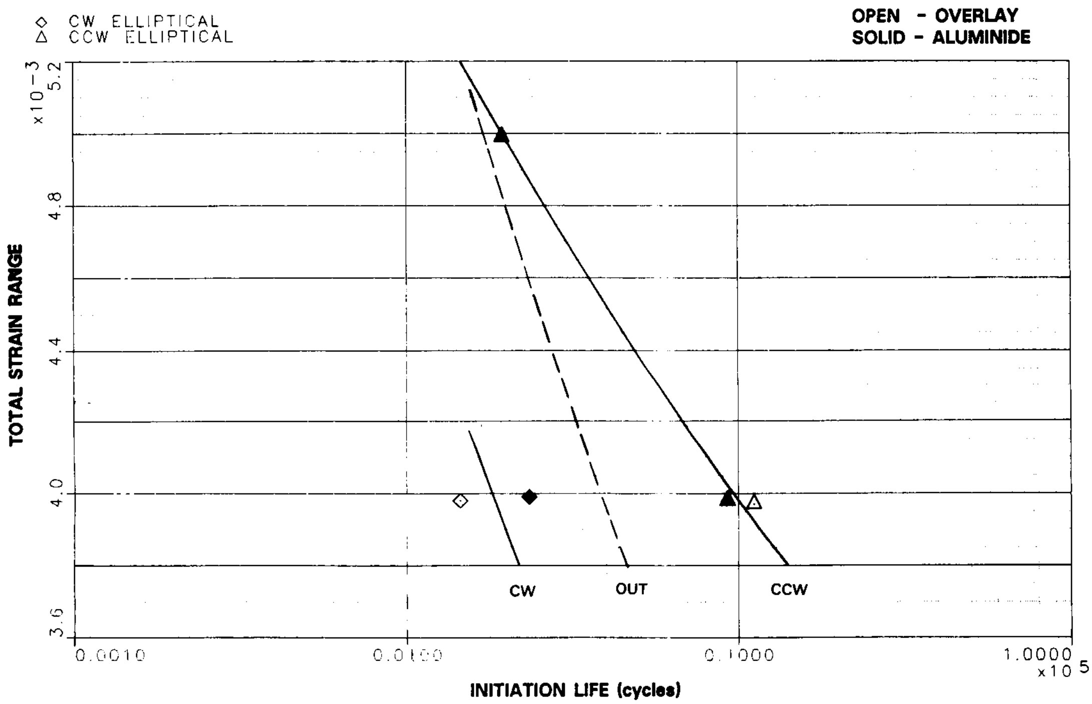
Ten baseline coated TMF specimen tests were completed at two nominal strain ranges, using both in-phase and out-of-phase cycling. The temperature range was 538-871°C (1000-1600°F), and the cyclic rate was 1 CPM. Both fully reversed and one-way compression strain cycles were used, but there was no obvious effect of mean strain on specimen life. A plot of initiation life vs. total mechanical strain range is shown in Figure 1, along with median life lines from uncoated TMF tests at the same conditions. Note that the coated data lie approximately 2X higher in life than the uncoated data, indicating that for these conditions, the coatings reduced the damage done by mechanisms such as oxidation. It is known, however, that the reverse is often true: coatings can themselves reduce the life under certain TMF strain cycles. For example, a "dogleg" cycle overlay coated specimen test was also run, using a non-isothermal strain hold at the minimum cycle strain combined with a rapid (6 second) fully reversed isothermal strain excursion at the minimum temperature. This test produced an initiation life which was lower than what had been observed for an uncoated specimen. This once again serves to emphasize the need to understand and model the actual damage mechanisms active under these conditions. Simple data correlations based on one or the other cycle type may not always give conservative predictions.

Perhaps the most interesting results obtained during this task are those from the elliptical cycle tests (strain and temperature are sinusoidal with time and shifted in phase by $\pm 135°$). Five coated specimen tests were completed under this series, including two clockwise (CW) and three counterclockwise (CCW) cycles. The CCW cycle is a good simulation of the strain-temperature history experienced by many actual hot section components. Although there are some components which have a CW movement around their strain-temperature history, the CW cycle results are most valuable when compared to the CCW results; the only apparent difference is the direction of motion around the loop. Figure 2 shows a plot of the elliptical test results for the coated specimens relative to the median lives from the out-of-phase coated tests. It is clear that there is approximately a 5X initiation life difference between the two types of cycles. Note that life prediction methods based solely on the extremes of the cycle will not be able to predict this behavior, since they cannot distinguish between these two cycles. To account for such cycle dependent effects, an advanced incremental form of the CDA life prediction model is under development which can be integrated around any arbitrary strain-temperature history curve. Four other coated specimens were also run using various types of TMF cycles involving both isothermal and non-isothermal hold times. These also showed strong effects of cycle path on initiation life.



IN-PHASE AND OUT-OF-PHASE TMF TESTS
(PWA 1455, 1000-1600°F, 1 CPM)

FIGURE 1



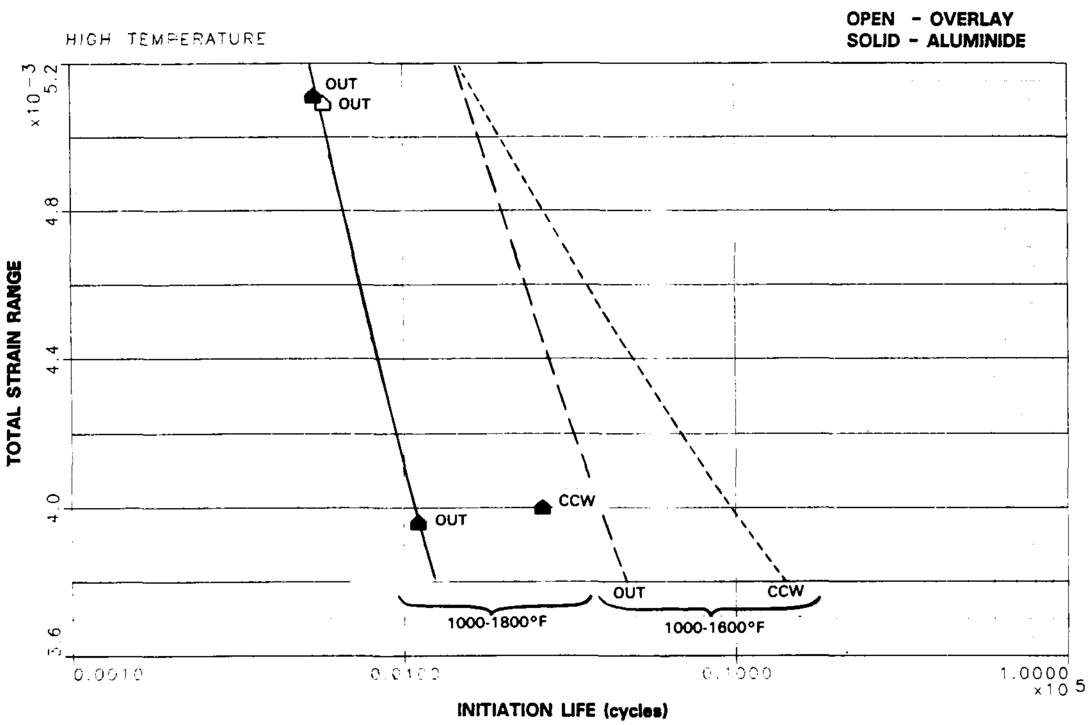
ELLIPTICAL CYCLE TMF TESTS
(PWA 1455, 1000-1600°F, 1 CPM)

FIGURE 2

Four other coated specimens were run at a higher temperature range (1000-1800°F) to determine if trends seen at the baseline temperature range would still hold true. Figure 3 shows these results, and all the data are seen to be shifted lower in life than the median data at the baseline temperatures. However, note that the life increase for an elliptical cycle relative to an out-of-phase cycle is still present.

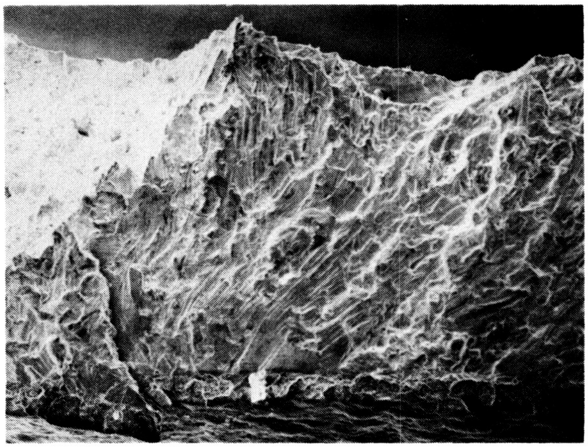
Figures 4 and 5 show optical micrographs of fracture surfaces typical of those observed during the coated TMF testing. In general, the fracture surfaces were heavily oxidized, making exact determination of the location of the crack origin difficult. However, the typical crack initiation site was in the coating surface, often accompanied by either localized porosity or small allowable defects in the coating. The lives from specimens which failed from ID-initiated cracks were adjusted to reflect the growth of cracks on the coated OD surface only.

Several modifications to the basic Cyclic Damage Accumulation life prediction model developed during the base program are being considered, including conventional cyclic variable methods and incremental techniques. Figure 6(a) shows a correlation of initiation life data from the uncoated TMF testing using total strain range alone, and Figure 6(b) shows the same data correlated using the stress range and the maximum stress as additional parameters as used by the CDA model. Figure 7 shows the same correlations for the coated TMF data. In both cases, the correlation is improved using the additional parameters, but obviously more work is needed to ensure good predictions in cases where no data is available for reference. Work is continuing on the incremental model, which is expected to be able to meet this goal.

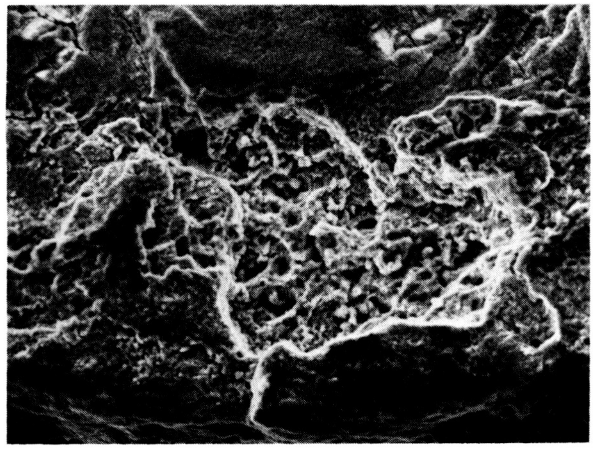


HIGH TEMPERATURE RANGE TMF TESTS
(PWA 1455, 1000-1800°F, 1 CPM)

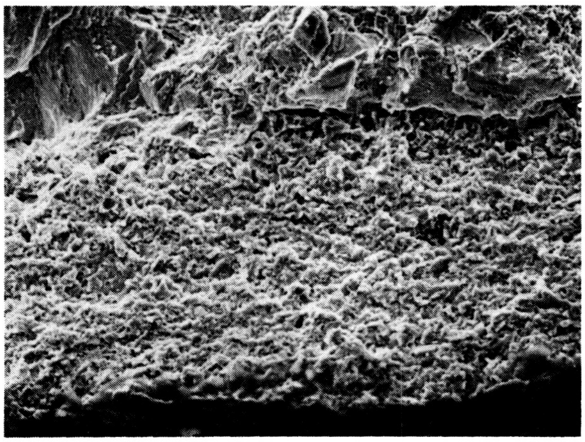
FIGURE 3



(a) 0.5 mm 50X



(b) 40 μm 500X

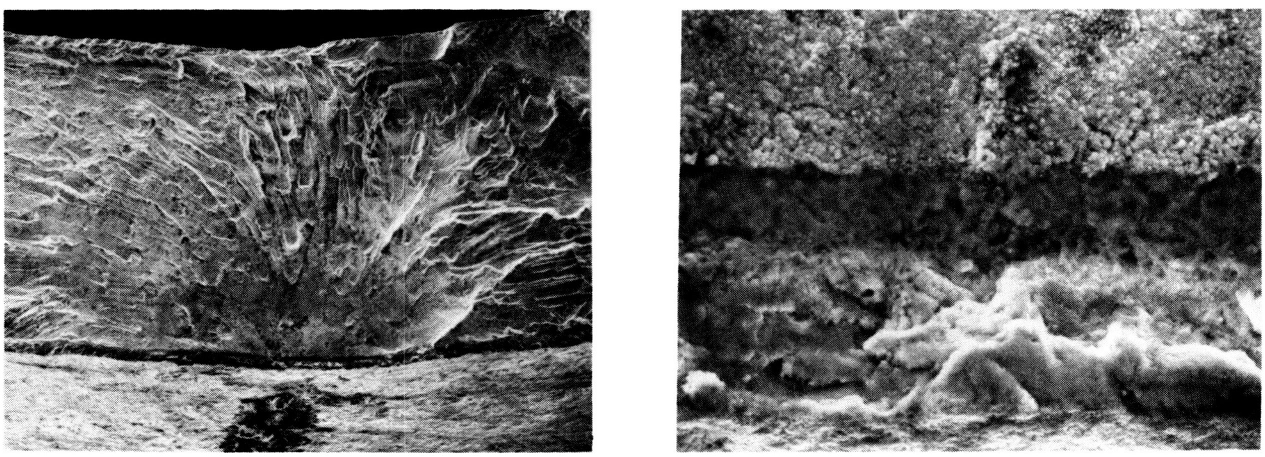


(c) 40 μm 500X

PWA 286 COATED TMF SPECIMEN 120B. Cycle I, $\Delta\varepsilon = 0.4\%$, 1000-1600°F, R=-1, INITIATION LIFE = 2938 CYCLES.

(a) SEM Micrograph of O.D. Initiation Site.
(b) Higher Magnification of (a) Showing Porous Appearance of Coating in Initiation Area
(c) SEM Micrograph of Coating in Area Fractured at Room Temperature

FIGURE 4

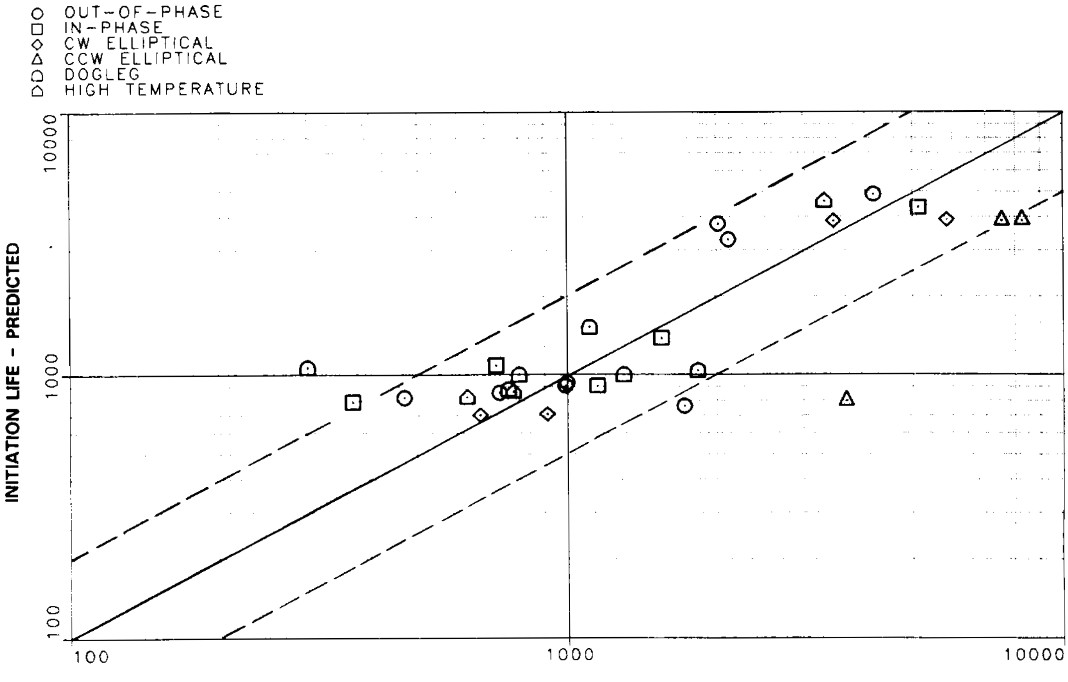


0.5 mm 50X

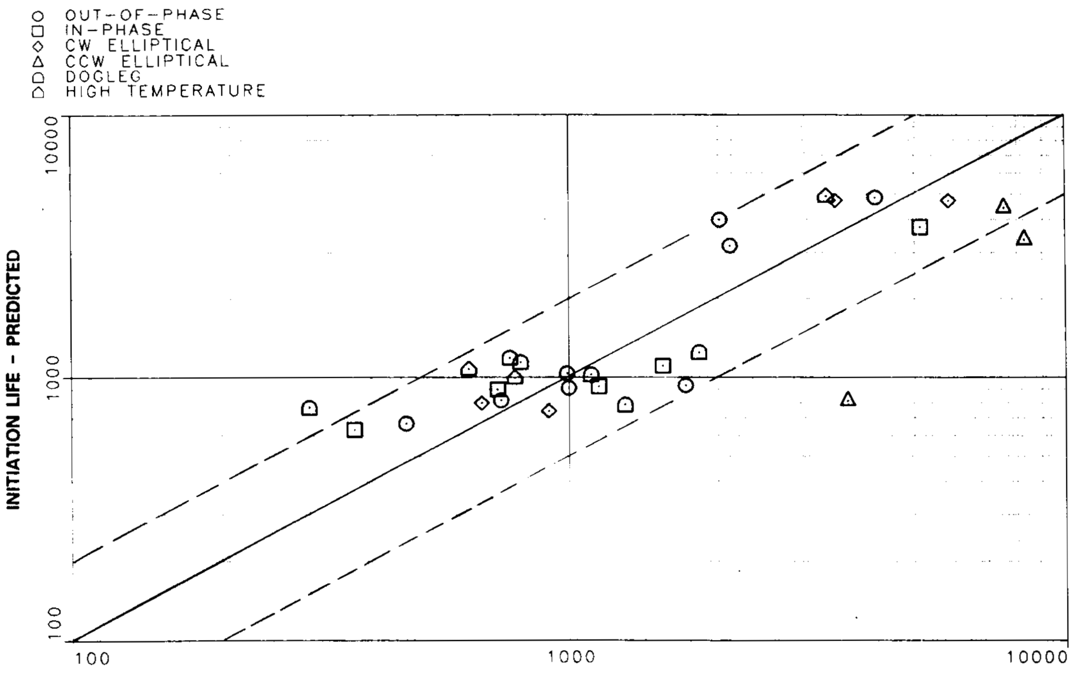
20 μm 1000X

PWA 273 COATED TMF SPECIMEN 114A. Cycle I, $\Delta\varepsilon = 0.4\%$, 1000-1600°F, R=1, Initiation Life = 4753 Cycles. SEM Micrographs of Primary O.D. Initiation Site. Dark Band Between Coating and Base Metal is the Diffusion Zone.

FIGURE 5



(a) TOTAL STRAIN RANGE



(b) PRELIMINARY CDA MODEL

TMF LIFE MODEL COMPARISONS FOR UNCOATED PWA 1455

FIGURE 6

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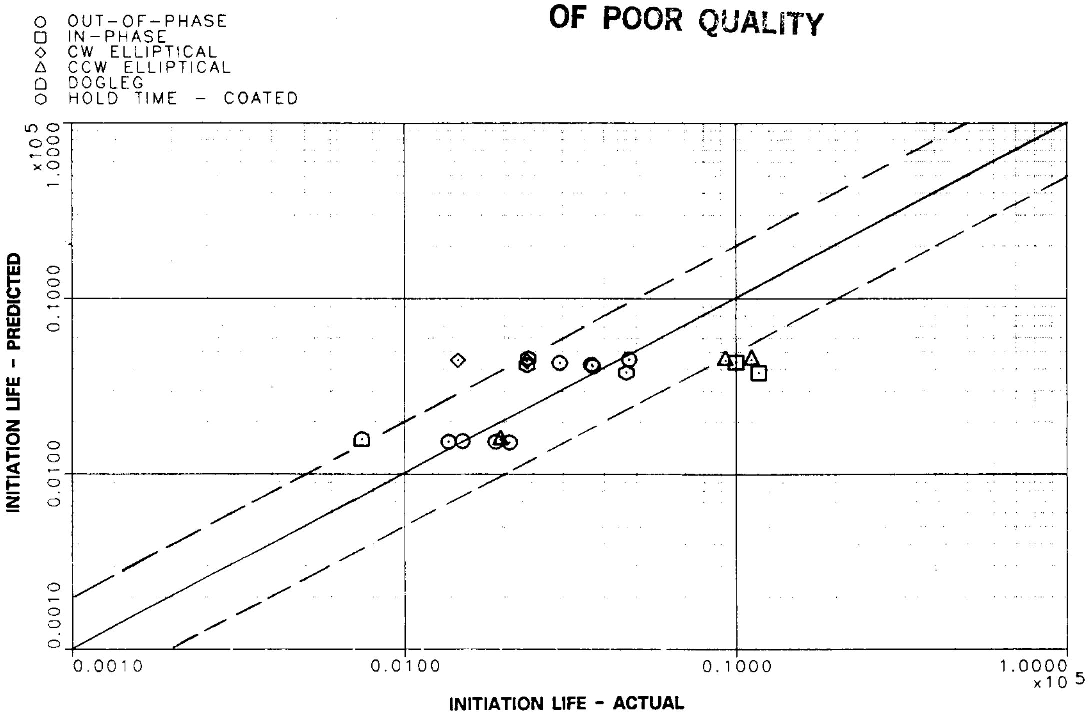
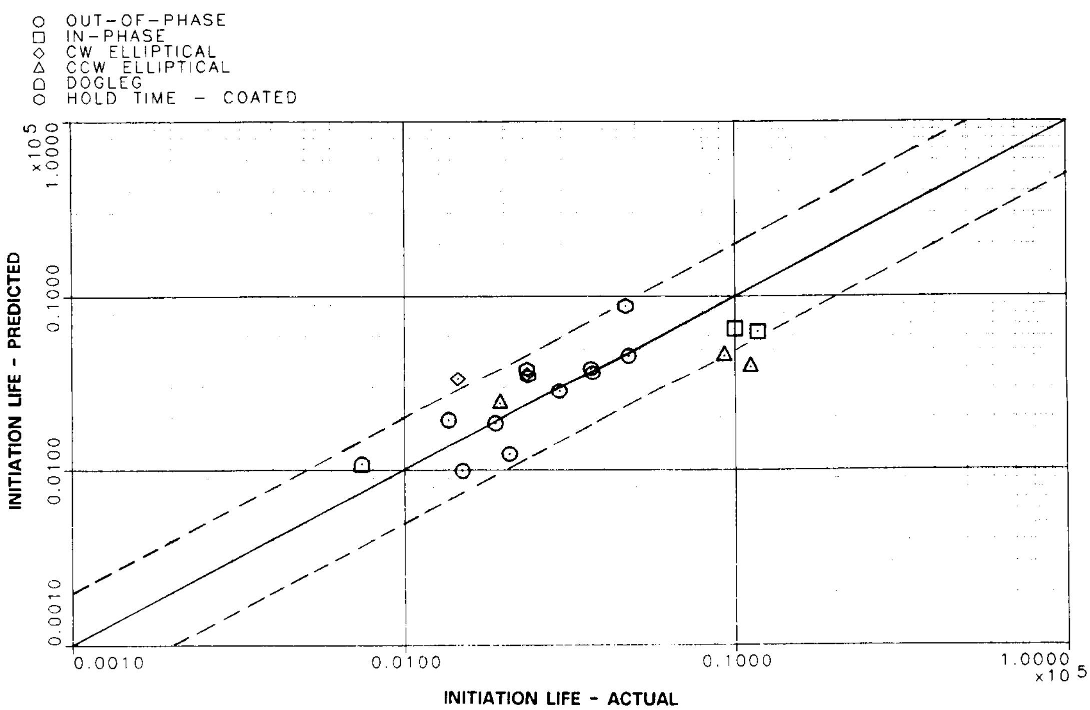
OF POOR QUALITY



(a) TOTAL STRAIN RANGE



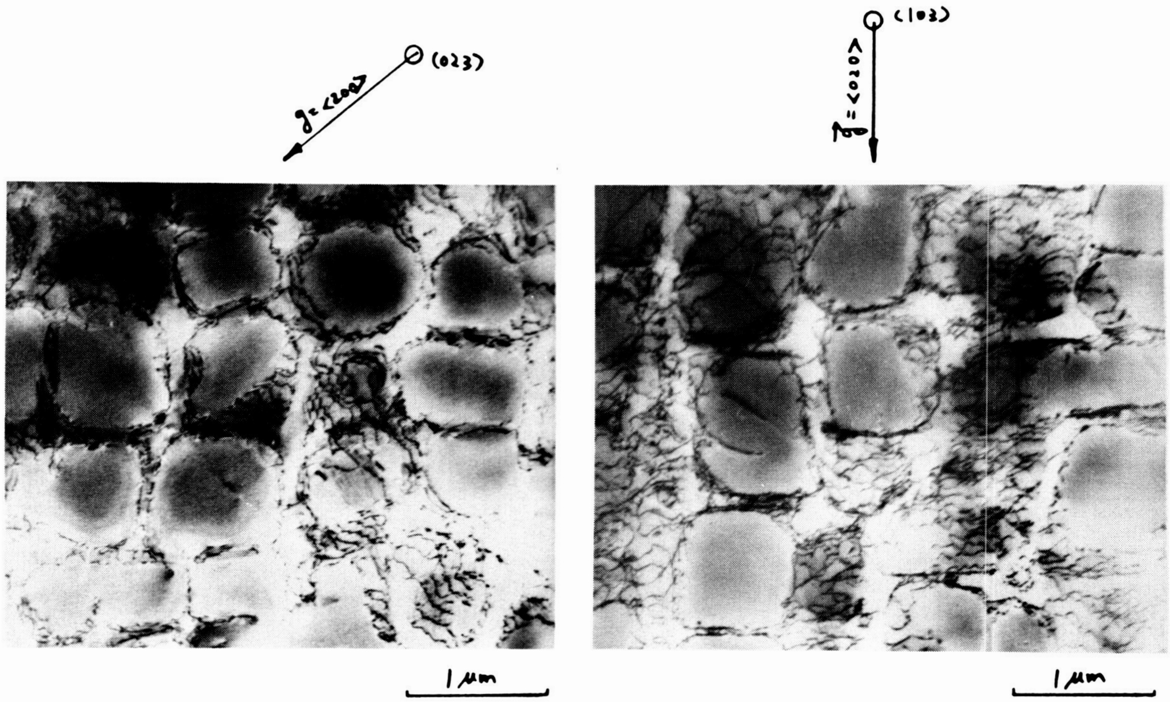
(b) PRELIMINARY CDA MODEL

TMF LIFE MODEL COMPARISONS FOR COATED PWA 1455

FIGURE 7

MULTI-AXIAL STRESS STATE MODEL

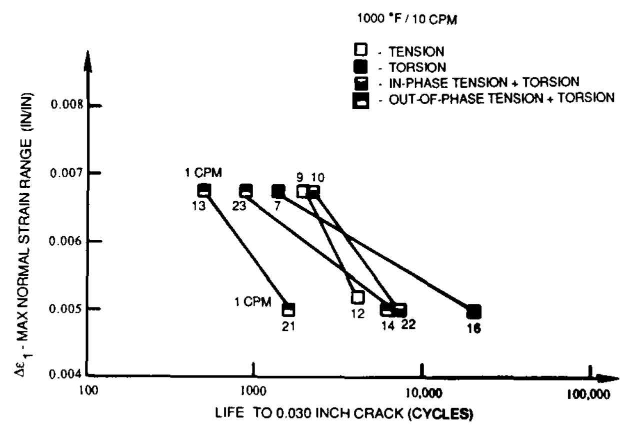
The specimen testing portion of this task has now been completed, comprising a total of 26 tests using thin-walled (0.050 in.) tubular specimens. Four types of strain cycles were employed in these tests: simple tension, simple torsion, combined in-phase tension-torsion (proportional loading), and combined 90° out-of-phase tension-torsion (non-proportional loading). The torsion-to-tension ratio was 1.5 for all the combined strain tests. The additional variables investigated were temperature, strain range, and strain rate. Figure 8 shows a typical dislocation structure for an out-of-phase, non-proportional test, showing wavy dislocation segments that are roughly parallel to one another and surrounding the gamma prime particles. This structure is similar to what was observed following both pure torsion and in-phase proportional tests.



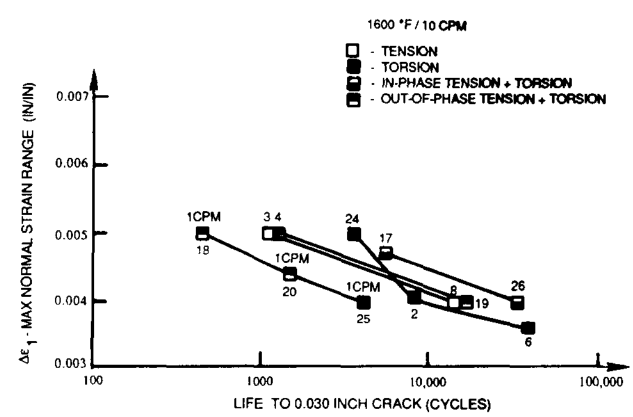
MULTIAXIAL SPECIMEN 216 DISLOCATION STRUCTURE AFTER 90° OUT-OF-PHASE TENSION-TORSION TESTING (1600°F, $\Delta\varepsilon = \pm 0.250\%$, $\Delta\gamma = \pm 0.375\%$, 90° Out-of-Phase, 10CPM, Initiation Life = 1250 Cycles, Total Test Life = 1973 Cycles).

FIGURE 8

Several data correlation methods have been investigated for the multiaxial loading tests, including equivalent strain, maximum shear strain, plastic work, and maximum normal strain range. The first three parameters had only limited success, due in part to their inability to predict correctly the somewhat higher lives resulting from the pure torsion tests. Also, the data showed very little cyclic inelasticity, which made any theory based on inelastic quantities very difficult to apply. Figure 9 shows the results of the testing at both 1000°F and 1600°F correlated using maximum normal strain range. The data is fairly well grouped, with the out-of-phase tests and the axial data being the lowest. The in-phase tension-torsion and the simple torsion tests still tend to be somewhat higher than the other conditions, but the sample size is too small to draw statistically significant conclusions. Note that the effect of cyclic rate is evident at both temperatures; no effect of cyclic rate was observed during the baseline uniaxial testing at 1000°F.



Maximum Normal Strain Range vs Cyclic Life
(a) 1000°F Tests



Maximum Normal Strain Range vs Cyclic Life
(a) 1600°F Tests

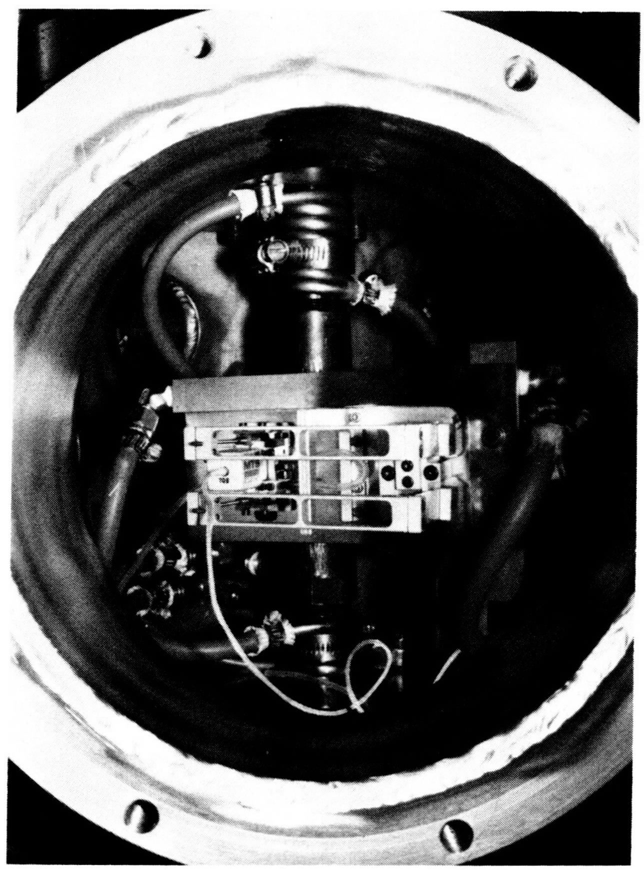
PWA 1455 MULTIAXIAL TESTS

FIGURE 9

ENVIRONMENTAL ATTACK MODEL

A controlled atmosphere creep-fatigue test matrix with 27 specimen tests has been determined for this task. The initial 9 screening tests are being conducted in three different environments: lab air, high pressure oxygen (same partial pressure as encountered in high pressure turbines), and high purity argon. The remaining 18 tests will use the environment which produces the largest effect and will examine sequence effects to support development of an advanced life model which can account for the observed life trends.

The stainless steel, low pressure chamber for this task has been completed and overpressure tested. Figure 10 shows the water-cooled MTS extensometer in place in front of the specimen. A total of 8 initial screening tests in lab air and 75 psia oxygen have been completed at baseline conditions at both 1600 and 1800°F. The lives in the high pressure oxygen are less than half of the baseline values for the slow rate tests, indicating a strong environmental effect on fatigue life under these conditions. The chamber has now been fitted with a Centorr argon purifier to assure very low oxygen levels, and initial trials show that the environment is satisfactory.

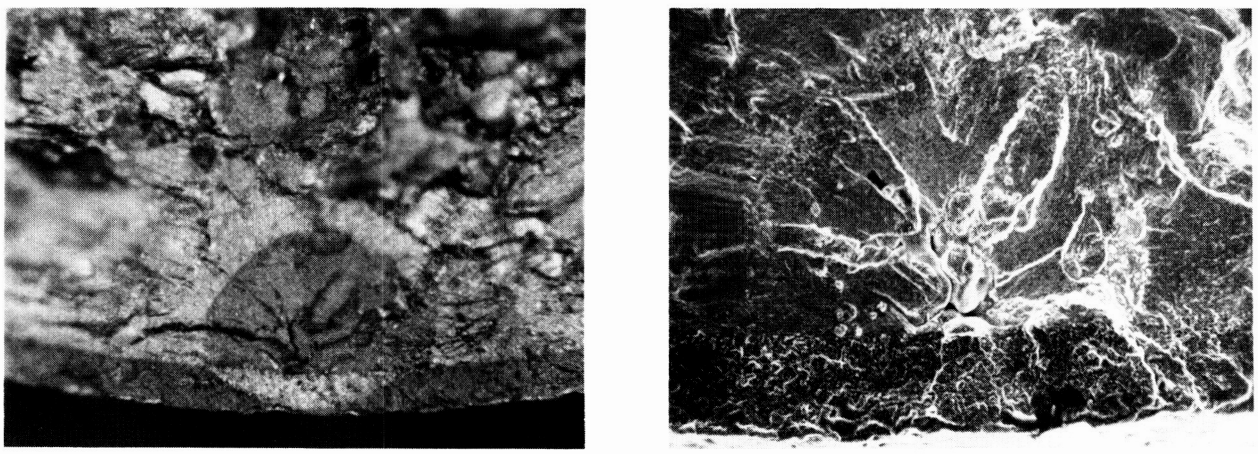


WATER COOLED EXTENSOMETER IN ENVIRONMENTAL TEST CHAMBER

FIGURE 10

PROTECTIVE COATINGS MODELS

A total of 8 overlay coated specimen tests have been completed. The coated specimens showed initiation lives which were 2X-7X higher than the lives of uncoated specimens run at similar conditions. Apparently the effect of oxidation was significantly reduced by the coating, so long as the ductility of the coating was not exceeded. For example, Figure 11 shows a specimen which experienced initiation from typical porosity in the B1900+Hf substrate. The crack clearly propagated outward from the substrate toward the specimen surface. This requires a two-mode model to capture correctly both coating and substrate initiation lives. The coating life model being developed under a companion HOST contract (reference 2) is being considered for integration with the CDA model to accomplish this capability.



(a) 0.5 mm 64X

(b) 100 μm 150X

SPECIMEN 117A (1600°F, $\Delta\varepsilon = 0.5\%$, R=0, 10 CPM, Initiation Life = 3799 Cycles, Separation Life = 4041 Cycles).

(a) Optical and (b) SEM Micrographs Showing Crack Origin at Porosity in the Base Material.

FIGURE 11

CYCLIC MEAN STRESS MODEL

A total of 25 controlled mean stress tests are planned for this task, including five under TMF conditions. All five TMF tests have been completed, using load control to achieve the desired mean stress. The results show that the lives under such conditions can be much lower than what might be expected from a linear combination of creep and TMF damage. The isothermal portion of this testing will be conducted by Prof. Ghonem at the University of Rhode Island. Initial specimen trials have been completed at the URI lab and have demonstrated their capability to reproduce P&W results under baseline conditions.

ALTERNATE MATERIAL TESTING

A total of 10 isothermal fatigue tests using INCO 718 material have now been completed. The results so far suggest that the particular ring-rolled AMS 5663 forging used to produce these specimens has excellent creep resistance as well as good fatigue capability. Tests at 1200°F show little difference between 30 CPM and 1 CPM cyclic rates. Creep, tensile, and multiaxial tests are also underway, with a view to developing the constants needed for the CDA life model. Of particular interest will be the influence of the pronounced cyclic softening noted during all the fatigue testing. It is expected that some modification to the form of the CDA model will be necessary to account for this.

FUTURE TASKS

Further work is continuing on all the above tasks, with the goal of producing a creep-fatigue model, which is both practical and accurate. During the last year of the contract effort, the focus will continue to shift from generation of test data to analytical model development activities. The generation of CDA model constants for INCO 718 will be completed, followed by additional refinement of the CDA life prediction model.

REFERENCES

1. Moreno, V., Nissley, D. M., and Lin, L. S., " Creep Fatigue Life Prediction for Engine Hot Section Materials (Isotropic) - Second Annual Report," NASA CR-174844, March 1985.

2. Swanson, G. A., Linask, I., Nissley, D. M., Norris, P. P., Meyer, T. G., and Walker, K. P., " Life Prediction and Constitutive Models for Engine Hot Section Anisotropic Materials Program - Second Annual Status Report," NASA CR-179594, April 1987.